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TH-3 Microwave Radio System:

Modulators

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In a TH-3 repeater the required frequency downconversion, upconversion, and shift is performed by three similar solid state modulators. The choice of an unbalanced design resulted in a simple modulator microwave structure which can be easily tuned and uniformly reproduced. The shift and transmitter modulators use a varactor diode for high pump efficiency while, in the receiver modulator, a Schottky diode is used to achieve a low noise figure and broadband operation.

I. INTRODUCTION

The TH-3 radio repeater makes use of three modulators: a receiver modulator for frequency downconversion, a shift modulator for frequency translation, and a transmitter modulator for frequency upconversion. These are unbalanced solid state modulators having different IF circuits and electrical requirements but similar microwave structures. Each of these modulators consists of two die-cast aluminum parts, one for the microwave structure and the other for the IF circuits.

The receiver modulator is used to downconvert the received microwave signal and to preamplify the 70-MHz IF signal before it is fed to the IF main amplifier for further amplification. Since the receiver modulator is the first active device to act upon the received microwave signal, it was designed primarily to obtain the highest possible carrier-to-noise ratio consistent with good transmission performance and reliability.

The transmitter modulator converts the 70-MHz frequency-modulated IF signal to a microwave signal having an upper and a lower sideband. The upper sideband is selected by an external microwave filter and fed to the TWT amplifier for further amplification prior to

transmission. The transmitter modulator was also designed with special attention toward transmission performance, reliability, and ease of tuning.

In a TH-3 repeater, the frequency plan requires a 252-MHz difference between the received and transmitted signal. As a result, separate local oscillator signals are required for the receiver and transmitter modulators. For reasons of system stability and economy, it is desirable to use a single microwave generator as a source of local oscillator signals. A shift modulator is therefore used to combine a portion of the local oscillator signal with a 252-MHz signal and to produce an output signal having two sidebands, one 252 MHz above and one 252 MHz below the applied local oscillator signal. The desired upper or lower sideband is then selected by an external microwave filter and serves as the local oscillator signal for the receiver modulator. Because of the shift modulator conversion loss, the shift modulator is used in the receiver where the local oscillator signal level required to drive the receiver modulator is considerably lower than the level required to drive the transmitter modulator.

II. THE RECEIVER MODULATOR

The design of the receiver modulator was patterned after an earlier design successfully used in a 4-GHz radio system.[1] As in the case of the other TH-3 modulators, this unit consists primarily of a diode mounted in a reduced-height waveguide structure followed by an IF preamplifier circuit. The local oscillator and received microwave signals are applied to the receiver modulator through an external microwave directional filter. The microwave structure and associated IF circuitry were primarily designed for low noise and therefore use a low-noise Schottky barrier diode (WECo 497A) and input transistor (WECo 45J) respectively.

2.1 *The Microwave Structure*

The receiver modulator uses an unbalanced microwave structure which, because of its simple design, was possible to construct using die-casting techniques which resulted in a uniform product requiring a minimum of machining. As illustrated by Fig. 1, the structure consists of a full-to-reduced-height waveguide step transducer followed by an 8-GHz waffle-iron lowpass filter and a diode mounted in a reduced-height waveguide cavity terminated by a waveguide short. The diode is physically mounted between a coaxial short, which is also the diode holder, and one end of a 5-GHz coaxial lowpass filter.

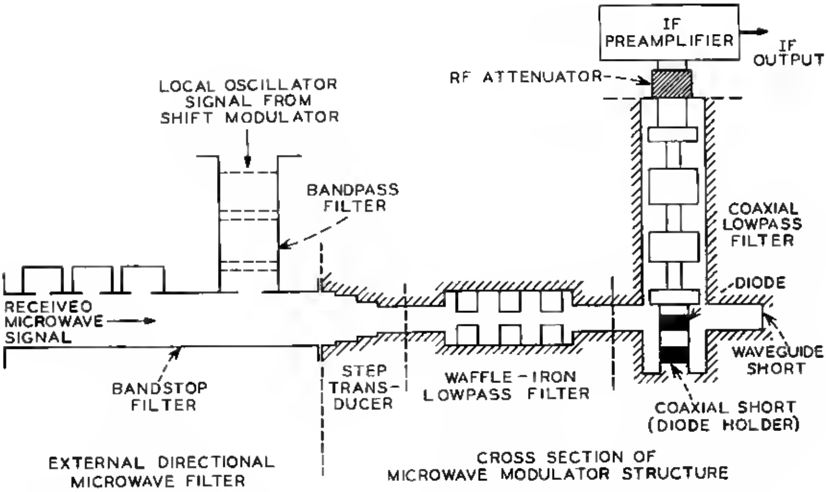

Fig. 1—Basic arrangement of receiver modulator and IF preamplifier assembly.

The coaxial filter has an RF attenuator consisting of a cylindrical bead of microwave lossy material inserted at one end of its center conductor. This attenuator is used to provide additional loss at frequencies above 5 GHz. The combined insertion loss of the coaxial filter and RF attenuator is approximately 3 dB at 0.8 GHz and 50 dB at 6 GHz. The waffle-iron filter has an insertion loss of approximately 3 dB at 8.2 GHz and 40 dB at 12 GHz.

The 5-GHz coaxial lowpass filter presents a high impedance to the input microwave signals thus assuring efficient application of these signals to the diode. The applied microwave frequencies mix in the diode to generate the desired 70-MHz IF difference frequency as well as other products and harmonics of the input signals. Harmonics of the input signals are restricted within the diode cavity by the waffle-iron filter, while the 70-MHz IF signal is applied to the IF preamplifier through the coaxial lowpass filter which is designed to provide a good impedance match to the diode at 70 MHz. The distance which the coaxial short (diode holder) extends into the diode cavity and the position of the waveguide short were experimentally determined to achieve the desired conversion efficiency and in-band stability. DC bias to the diode is applied through the coaxial filter from a network in the IF preamplifier circuit.

The various components required to make up the microwave structure of a transmitter modulator (essentially identical to that of a receiver modulator) are shown in Fig. 2. The structure is precision die

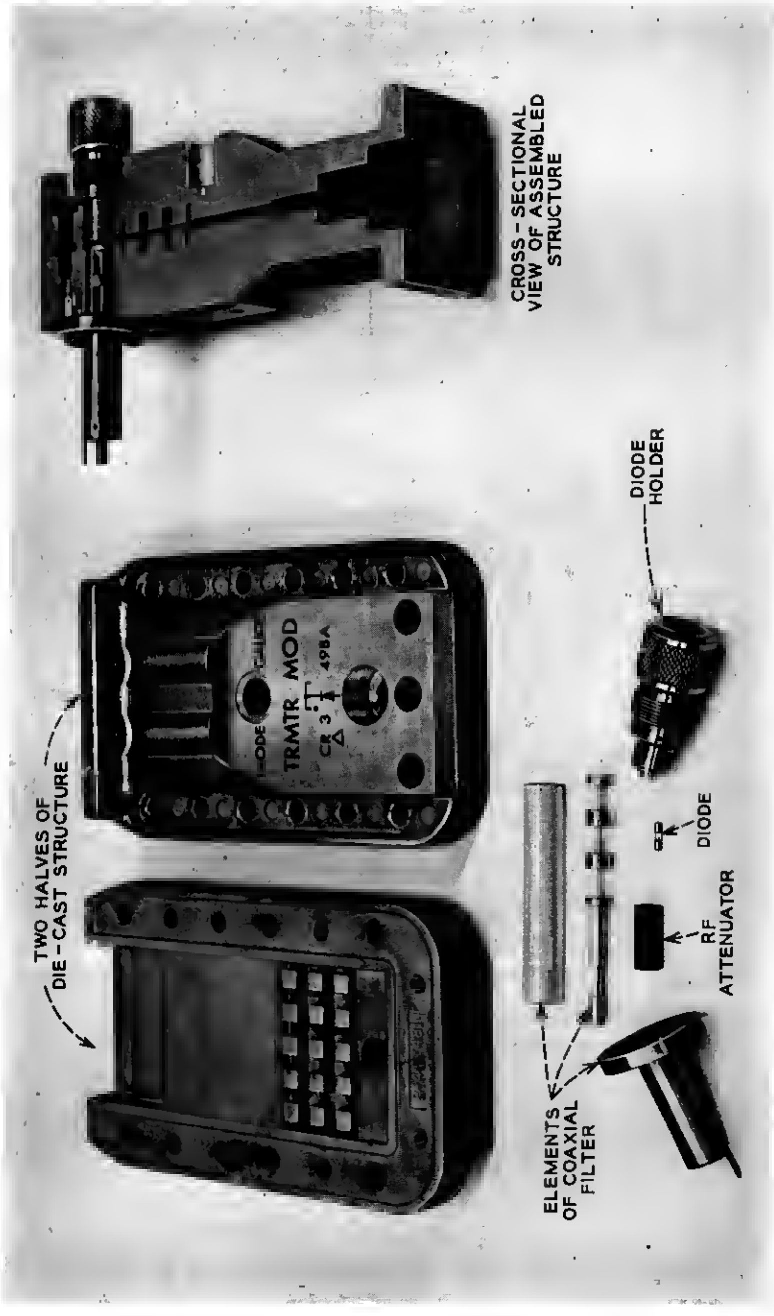

Fig. 2—Sectionalized microwave structure.

cast into two identical halves. It is then machined to accept the diode holder on one side and the coaxial filter on the other. Referring to Fig. 2, a diode gauge hole is machined to a specific depth on the face of one side of the structure. This hole is used to set the distance which the diode protrudes from the diode holder so that when the diode holder is inserted, proper mating of the diode with a small star chuck at the inner end of the coaxial filter is assured.

Typical microwave-to-IF conversion loss of the microwave structure is 4 dB. The nominal local oscillator and received microwave signal levels applied to the structure are +6 and −23 dBm respectively.

2.2 *The IF Preamplifier*

The receiver modulator, shown in Fig. 3, converts the incoming microwave signal into an IF signal with approximately 17 to 27 dB of gain. The IF preamplifier has a noise figure of approximately 2.5 dB and a maximum gain capability of 33 dB. As shown in Fig. 4, it consists of five transistor stages: a common emitter, a common emitter with shunt feedback, and three transformer-coupled common-base stages.

The 70-MHz IF signal taken from the coaxial lowpass filter is applied to inductor L1 or point A depending upon the channel frequency. Inductor L1 is used to improve the impedance match and thus the noise figure of modulators operating in the upper half of the TH-3 band; a wiring option bypasses the inductor in modulators operating in the lower half of the TH-3 band. The LEVEL control is used to set the output power level at −1.5 dBm for the range of inputs

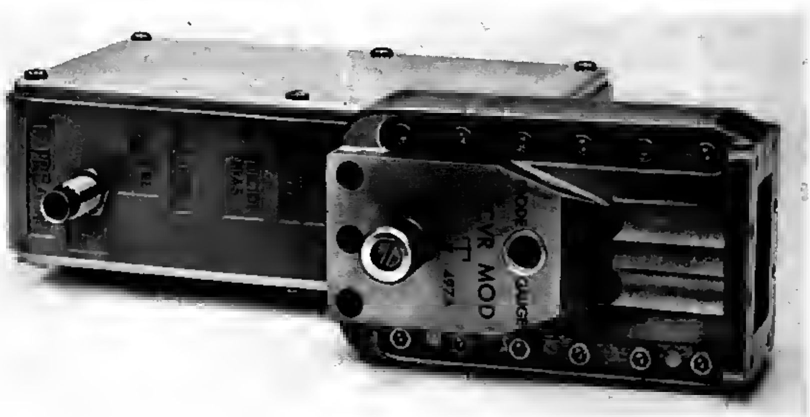

Fig. 3—Receiver modulator.

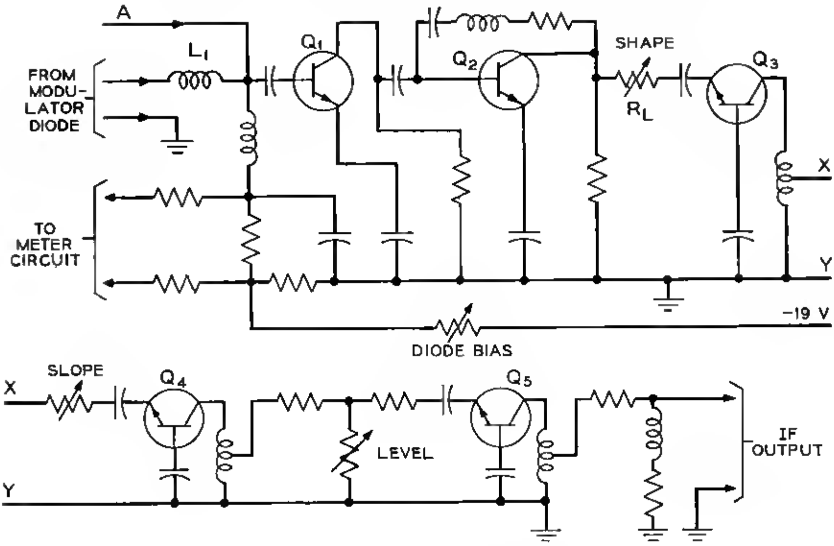

Fig. 4—IF preamplifier schematic.

expected for TH-3 repeater spacings, and has an adjustment range of about 10 dB. SHAPE and SLOPE controls are provided to adjust for flat RF-to-IF transmission. The overall transmission can be made flat to within 0.03 dB peak-to-peak deviation across the 30-MHz signal band. The output return loss is typically better than 30 dB across the same band.

The operation and method of applying the dc bias to the Schottky diode differs from that used in the earlier modulator design. In the earlier design, the diode bias network formed a constant current source. This method had the disadvantage of causing the modulator performance to be very sensitive to variations in local oscillator signal levels. It was found that an optimum bias network source resistance exists which is neither constant current nor constant voltage but which makes the modulator performance relatively insensitive to variations in the modulator local oscillator level. With the optimum source resistance for the bias network, the diode bias current varies with the local oscillator level so that the impedance of the Schottky diode remains relatively constant as the local oscillator level is changed. Measurements on a large number of diodes using this network showed that the optimum diode bias current, once set at the proper level for a given local oscillator level, is independent of the diode characteristics and of the channel frequency.

The DIODE BIAS potentiometer is adjusted to obtain the desired diode current for a given local oscillator level. Once the control is adjusted, changes in local oscillator level cause the diode current to vary as shown by the curve in Fig. 5. Provisions are also made to monitor the diode bias by an external meter circuit. Figure 6 shows the receiver modulator noise figure and IF output level sensitivity to variations in local oscillator level. Once set, the local oscillator level is not expected to vary by more than 1 or 2 dB; this variation is due mainly to temperature variations. However, a level drop as great as 6 dB does not cause an appreciable degradation (typically 0.04 dB) in the shape of the RF-to-IF transmission characteristic over the 30-MHz signal band.

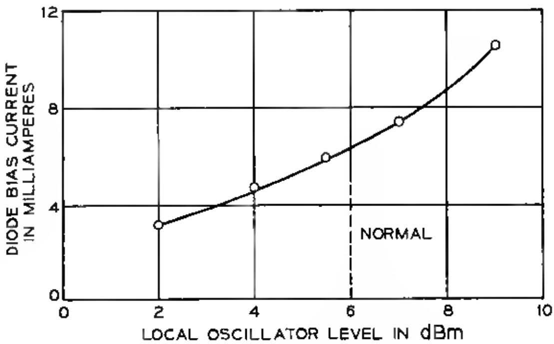

Fig. 5—Optimum diode bias current versus local oscillator level.

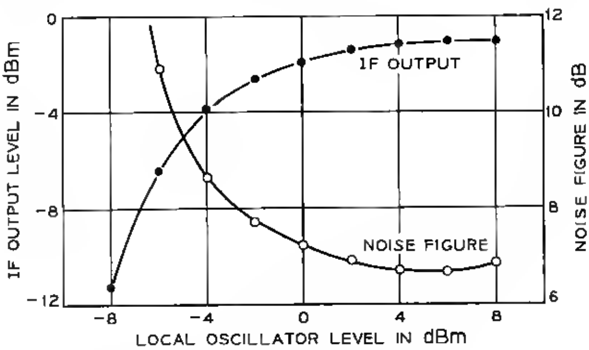

Fig. 6—Typical receiver modulator noise figure and IF output level sensitivity to variations in local oscillator level.

III. THE TRANSMITTER MODULATOR

The transmitter modulator, shown in Fig. 7, consists of an IF limiter amplifier followed by a single varactor diode mounted in a reduced-height waveguide structure. The modulator was designed for a nominal IF input level to the IF limiter amplifier of −7 dBm and a local oscillator microwave signal level of +18 dBm. The modulator was designed as an upper sideband upconverter to translate a 70 ± 15-MHz IF frequency band to any one of sixteen radio channels, each having a bandwidth of 30 MHz and a center frequency in range of 5945 to 6404 MHz. External circulators and a microwave bandpass filter are used to supply the correct local oscillator signal and to select the desired sideband respectively. Tuning to any one of the radio channels is accomplished by selecting the desired output bandpass filter and applying the associated local oscillator signal. The dc bias to the diode is then adjusted to tune the modulator to the desired channel.

An external squelch initiator circuit controls the output signal level of the transmitter modulator. This circuit provides, under extreme fading or absence of microwave carrier conditions, an overriding bias voltage to the varactor diode which detunes the microwave diode cavity and causes a decrease in the modulator output signal level. A more detailed explanation of the squelch function is given in a companion paper.[2]

3.1 *The Microwave Structure*

The transmitter modulator uses an unbalanced microwave structure design, shown in Fig. 8, similar to that used for the receiver modulator.

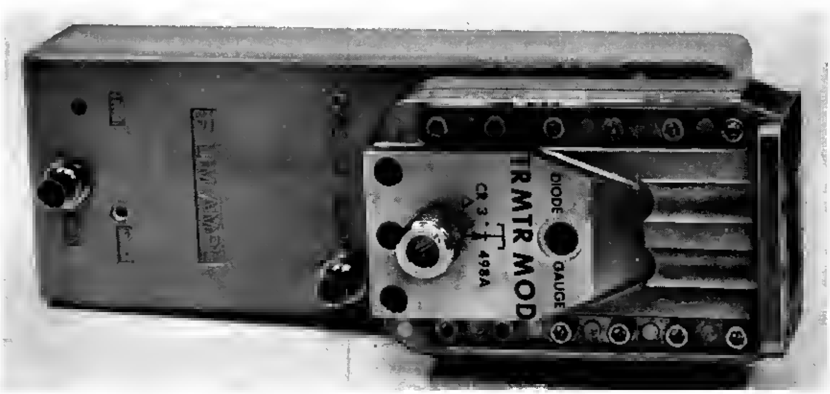

Fig. 7—Transmitter modulator.

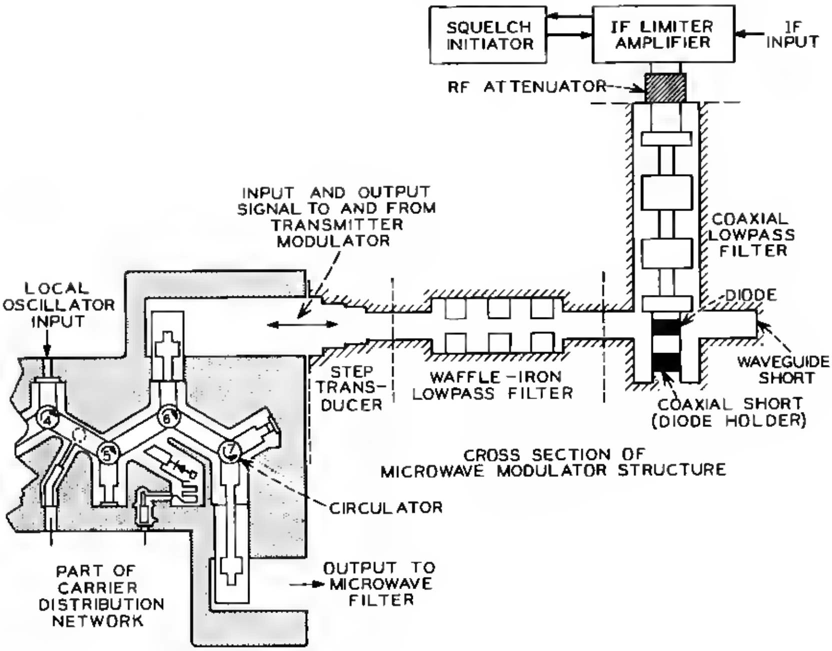

Fig. 8—Basic arrangement of transmitter modulator, IF limiter amplifier, and squelch initiator assembly.

The microwave structures of the two modulators differ only in the position of the waveguide and coaxial shorts and in the characteristic impedance of the coaxial lowpass filter which, in this case, was optimized to match the varactor diode. The WECo 498A varactor diode, rather than a varistor, is used in the transmitter modulator because of its greater upconversion efficiency. In addition, it was desirable to use the upper sideband exclusively for both maximum efficiency and stability, although, from a system viewpoint, it would have been more desirable to use both the upper and the lower sideband.

Referring to Fig. 8, the local oscillator signal is applied to an external carrier distribution network where it is routed to the input of the microwave structure by circulators 4, 5, and 6. The signal finally reaches the diode through the step transducer and waffle-iron lowpass filter. The 70-MHz modulated signal from the output of the IF limiter amplifier is applied to the diode through the coaxial lowpass filter. The waffle-iron structure presents a high impedance to the 70-MHz signal thus assuring efficient application of this signal to the

diode. Similarly, the coaxial lowpass filter presents a high impedance to the microwave signal thus assuring negligible absorption of RF power.

The mixing action of the diode generates frequencies of the type $nf_o \pm mf_i$.* The cavity in which the diode is situated, with its coaxial and waveguide shorts, reflects the RF modulated signal out through the waffle-iron lowpass structure and step transducer to the external carrier distribution network where it is routed to the external microwave filter by circulators 6 and 7. The desired upper sideband $(f_o + f_i)$ is routed to the TWT amplifier via the selective microwave bandpass filter. The lower sideband along with other undesired 6-GHz signals $(f_o - f_i, f_o \pm 2f_i, \cdots, f_o \pm mf_i)$ are reflected by the microwave filter and terminated by circulator 7 of the carrier distribution network. The harmonics of the 6-GHz signal $(nf_o \pm mf_i)$ are restricted to the diode cavity by the waffle-iron and coaxial lowpass structures and are dissipated in the resistive components of the cavity. With the diode at zero bias, the diode cavity is resonated at approximately 5.7 GHz by the waveguide short and the coaxial short. Varying the diode bias from -1 to -4 volts varies the quiescent capacitance of the varactor diode and tunes the structure to any frequency between 5.9 and 6.4 GHz. The nominal local oscillator level is +18 dBm, and the 70-MHz IF level applied to the varactor diode varies from +3 dBM at the low end of the TH-3 frequency band to +5.7 dBm at the high end of the band. This level range was found necessary to reduce the modulator expansion (more than a 1-dB drop in output signal level for a 1-dB drop in local oscillator input level) to a minimum. The pump-to-output-signal loss is less than 9.0 dB. The IF-to-microwave transmission characteristic typically deviates less than 0.02 dB from the output filter characteristic within ±15 MHz of the channel center frequency. The relative level of the various signal products appearing directly at the output of the transmitter modulator are shown in Fig. 9. The product at the frequency f_o + 70 MHz is the desired upper sideband which is selected by the microwave bandpass filter.

3.2 *The IF Limiter Amplifier*

The IF limiter amplifier is used to suppress the residual AM introduced by nonlinearities in various IF and microwave networks and active devices; it also provides the required IF drive level and dc

* Where f_o = local oscillator frequency, f_i = IF frequency, n = harmonics of f_o, and m = harmonics of f_i.

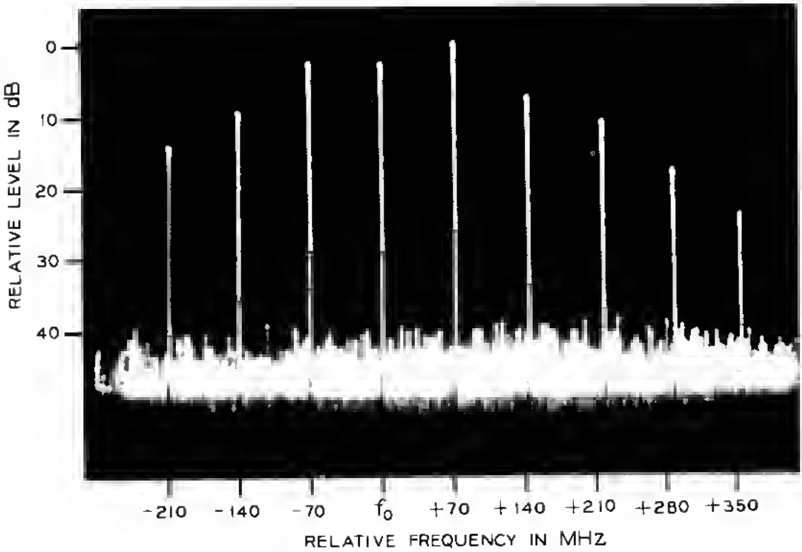

Fig. 9—Relative level of products at the output of the transmitter modulator.

bias for the modulator diode and a monitor signal to operate an external squelch initiator circuit. The IF limiter amplifier consists of a two-stage feedback amplifier at the input, a diode limiting section, and another feedback amplifier pair at the output to drive the varactor diode in the modulator microwave structure. As shown in Fig. 10, it utilizes series-shunt feedback pairs[3] as the basic gain stage for both the input and output amplifiers.

The two-stage input amplifier amplifies the −7-dBm IF input signal by approximately 10 dB. The resulting signal is then fed to the diode limiting section which consists of a series clipper limiter. The limiter was designed to provide a minimum of 20 dB of AM suppression while contributing less than 0.2 degree/dB AM-to-PM conversion. The diodes, CR1 and CR2, are 479A epitaxial silicon Schottky diodes used because of their low capacitance, fast reverse recovery time, and high back-to-forward resistance ratio.

The performance of the limiter is principally dependent upon the diode capacitance which is undesirable because it allows some signal transmission when the diodes are reverse biased. Because this leakage signal is 90 degrees out of phase with the signal transmitted through the diodes, it produces AM-to-PM conversion and degrades the AM suppression. To offset this effect, a balancing signal 180 degrees out

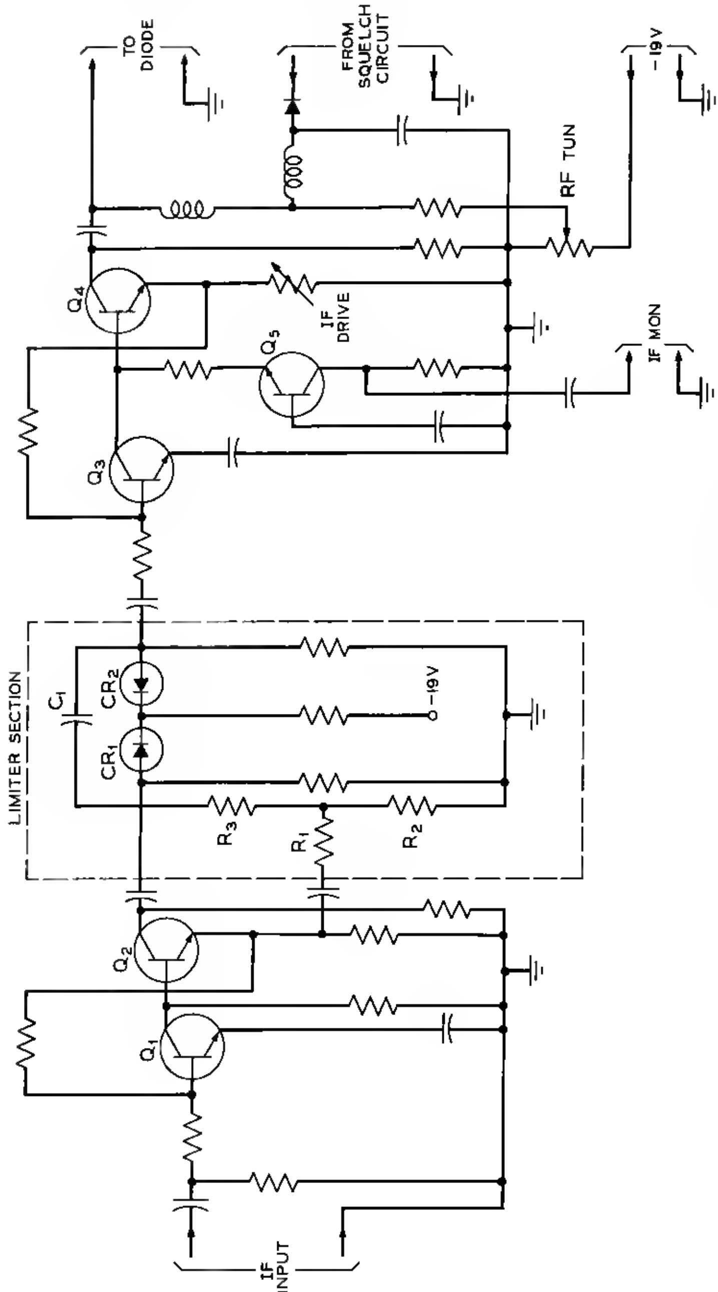

Fig. 10—IF limiter amplifier schematic.

of phase with the leakage signal is taken from the emitter of Q2 and ac-coupled to the resistor divider R1 and R2. These resistors were selected to determine both the ac gain of stage Q2 and the magnitude of the balancing signal. From this point the signal is fed to the output of the limiter through R3 and C1, the values of which were experimentally determined to obtain the desired 180 degrees phase difference. The loss of the 70-MHz signal through the limiter section is approximately 11 dB. The AM suppression and AM-to-PM conversion performance of the IF limiter amplifier are shown in Fig. 11. The output two-stage amplifier has from 10 to 14 dB of gain. The IF DRIVE control adjusts the gain of the output amplifier and is used to drive the modulator diode at the appropriate IF signal level. The RF TUN control is used to set the dc bias to the modulator diode.

The IF monitor delivers a sample of the output signal at approximately −14 dBm to the input of the external squelch initiator circuit. A common base stage provides isolation between the through-trans-

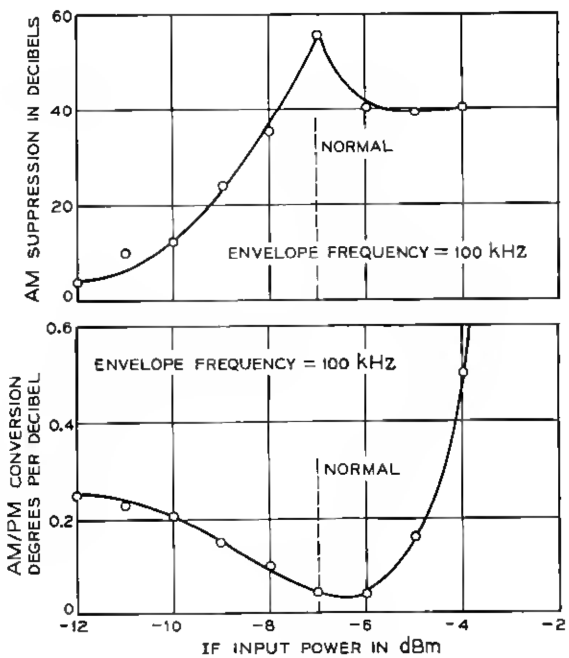

Fig. 11—Limiter AM suppression and AM/PM conversion versus input power.

mission path and the monitor circuit. An access lead is also provided to bias the modulator diode from the squelch initiator circuit.

The overall IF gain and noise figure of the limiter amplifier is approximately 9 to 13 dB and 16 dB respectively. Its transmission characteristic is designed to have a positive slope, typically 0.5 dB, over the 70 ± 15-MHz band.

3.3 *The Squelch Initiator*

The squelch initiator detects the noise level at the IF monitor point of the IF limiter amplifier. When the noise reaches a pre-selected threshold, this circuit generates a negative bias voltage which is fed back to the IF limiter amplifier and applied to the modulator diode.

This voltage is used to override the normal bias to the varactor diode resulting in a detuned diode cavity and a reduction of the microwave signal level at the output of the transmitter modulator, and thus at the output of the TWT amplifier. Figure 12 shows the squelch initiator unit housed in its aluminum casting.

Under normal operating conditions the 70-MHz IF signal from the IF MON jack of the IF limiter amplifier is applied to the input of the squelch initiator circuit at a level of −14 dBm. As shown in Fig. 13, the input signal is filtered by an 86-MHz bandpass filter which has a 3-dB bandwidth of about 2 MHz. The signal or noise appearing in this 2-MHz slot is amplified 73 dB by four series-shunt feedback pairs, each consisting of two high-frequency transistors.[3] The amplified noise is rectified and the resulting dc signal is used to trip a Schmitt trigger circuit. The output of the Schmitt trigger circuit controls the operation of a dc amplifier which provides a negative dc bias voltage for the modulator diode as well as for other alarm functions. The fading range or noise level required to trip the Schmitt trigger circuit is set by the TRIP control.

A 3-dB drop in transmitted signal level normally makes an external meter relay activate an output level alarm. However, when the drop in level is caused by the operation of the squelch circuit, most likely initiated by fading conditions or by a failure of a previous repeater,

Fig. 12—Squelch initiator.

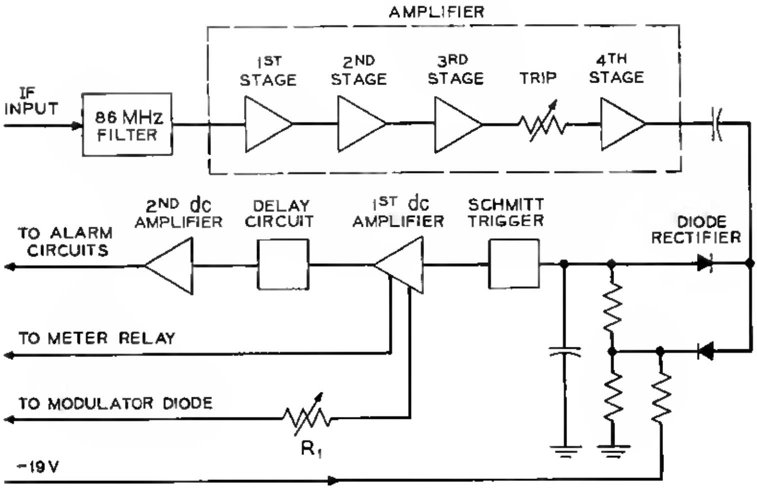

Fig. 13—Squelch initiator simplified schematic.

it is desirable to prevent the operation of the output alarm. This is accomplished by applying a dc bias voltage to the meter relay from the first dc amplifier. When the microwave carrier level is restored, the Schmitt trigger circuit automatically resets resulting in the removal of all dc voltages from the outputs of the dc amplifiers.

Variable resistor R1 is adjusted to provide the overriding bias required to cause a 29-dB drop in transmitted signal level.[2] The delay circuit and the following dc amplifier circuit activate an external alarm circuit 45 seconds after the application of the overriding bias voltage to the modulator diode.

IV. THE SHIFT MODULATOR

The shift modulator consists of an unbalanced microwave structure containing a varactor diode in a reduced-height microwave cavity. This unit is shown in Fig. 14. The unit is used to shift the frequency of a local oscillator microwave signal by ± 252 MHz. The upper or lower sideband output signal is used as the local oscillator signal for the receiver modulator. External circulators and microwave bandpass filters are used to apply the local oscillator signal, route the reflected output signal, and select the desired output sideband. The modulator microwave structure is designed to operate at a local oscillator signal level of +14 to +18.5 dBm and at a 252-MHz level of +6 dBm. This

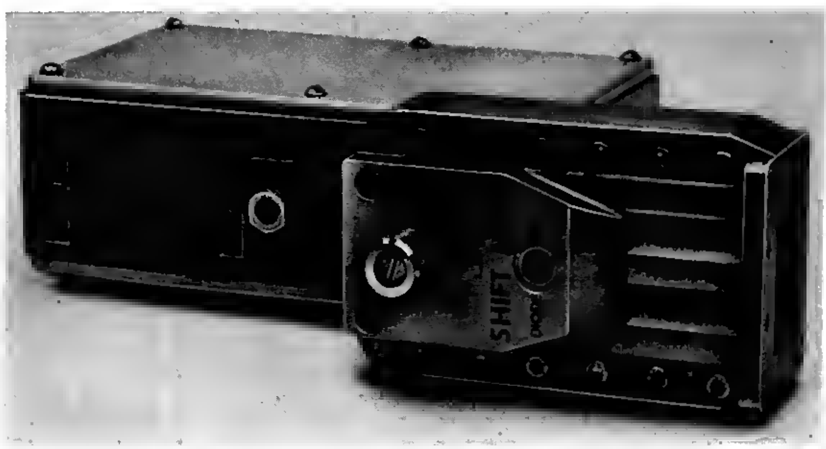

Fig. 14—Shift modulator.

modulator is tuned in the field by the use of a single adjustment which controls the bias applied to the varactor diode.

4.1 *The Microwave Structure*

The microwave structure and principle of operation of the shift modulator are identical to that of the transmitter modulator. As a result, the same structure with its associated diode and coaxial lowpass filter is used in both modulators. However, this structure was designed primarily to meet the more stringent electrical requirements of the transmitter modulator. The routing of the local oscillator signal to the input of the structure and the rerouting of its reflected output signal is accomplished in a manner similar to that illustrated by Fig. 8. Because the principle of operation and the microwave structure is the same in both modulators, the description which follows is kept more general than that given in Section III.

The 252-MHz shift signal from the shift oscillator is applied to the varactor diode through the coaxial lowpass filter. A portion of the local oscillator signal applied to an external carrier distribution network is routed by circulators within the network to the step transducer of the microwave structure. The signal then reaches the diode via the step transducer and waffle-iron lowpass filter. The mixing action of the diode generates two major signal sidebands, one 252 MHz above and one 252 MHz below the applied local oscillator signal, in addition

to other minor sidebands and harmonics of the applied signals. The upper and lower sideband signals are then reflected back out through the waffle-iron filter and step transducer and are routed to the microwave directional filter at the input of the receiver modulator by circulators within the carrier distribution network. The desired sideband, after being selected by the bandpass section of the directional filter, is used as the local oscillator signal for the receiver modulator, while the undesired sideband is reflected by the filter and terminated in a circulator within the carrier distribution network. The pump-to-output-signal loss is less than 9.0 dB.

4.2 *The Shift Oscillator*

The shift oscillator circuit generates a 252-MHz crystal-controlled signal used by the shift modulator to shift the common local oscillator microwave signal. As shown in Fig. 15, this circuit consists of a 126.0200-MHz oscillator, a frequency doubler, and a 252-MHz tuned amplifier.

The oscillator stage uses a seventh overtone crystal which operates at series resonance. The oscillator stability is within ± 1 kHz from -10 to $+140$°F. The FREQ MON jack at the output of the oscillator is used to monitor the frequency while in service. Potentiometer R1, which controls the output level over a 6-dB range, is provided at the output of the multiplier stage. This control is used to set the drive to the varactor diode at $+6$ dBm. The level of the 252 ± 126-MHz harmonic signal at the output is typically 40 dB down from that of the 252-MHz output signal. Adjustable bias to the varactor diode is provided by the RF TUN potentiometer. A portion of the 252-MHz output level is rectified by diode D1 and used by an external meter circuit for in-service monitoring of the oscillator. As in the case of the transmitter modulator, the shift modulator has only one field adjustment, the RF TUN control, the other controls being factory adjustments.

V. ACKNOWLEDGMENTS

The development of the TH-3 modulators was made possible by the combined effort of many individuals. Specifically, the author wishes to acknowledge the contribution of A. E. Dethlefsen for the initial development of the transmitter and shift modulator microwave structure, F. M. Klisch for the initial development of the receiver modulator microwave structure, D. A. Clark for his early work on the shift oscillator circuit design, G. H. Lentz for the squelch initiator circuit

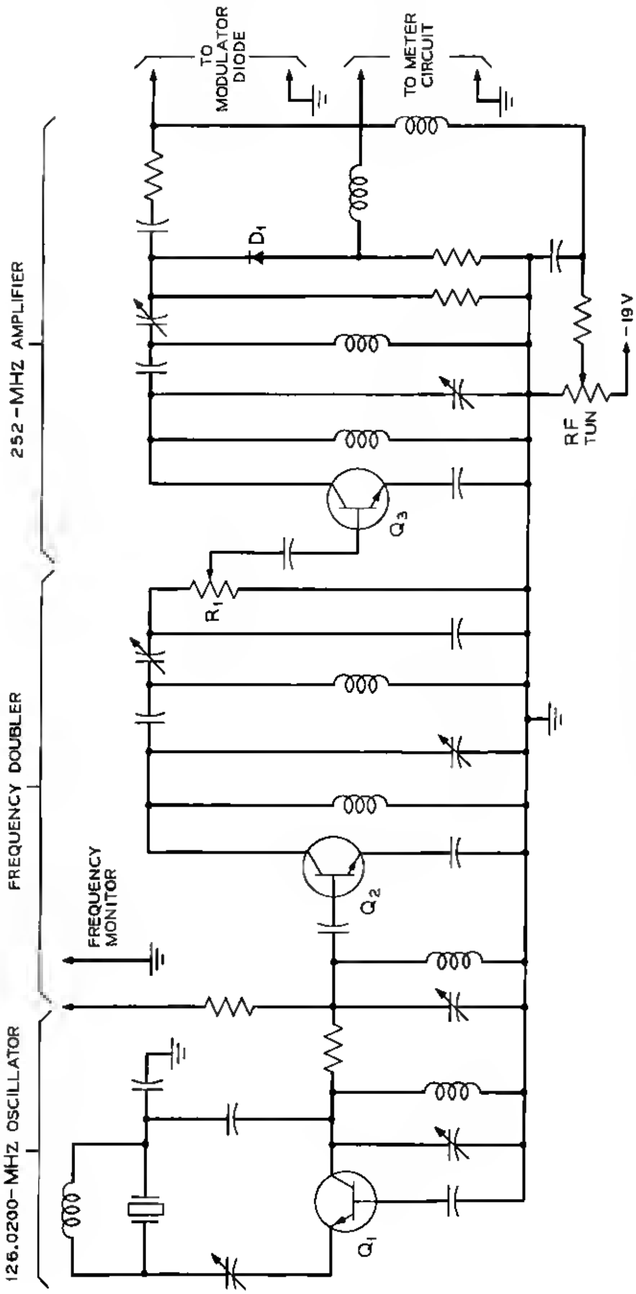

Fig. 15—Shift oscillator schematic.

design, and S. H. Lee for the design of the IF limiter amplifier and IF preamplifier circuits.

REFERENCES

1. Abele, T. A., Alberts, A. J., Ren, C. L., and Tuchen, G. A., "Schottky Barrier Receiver Modulator," B.S.T.J., *47*, No. 7 (September 1968), pp. 1257–1287.
2. Jansen, R. M., and Prime, R. C., "TH-3 Microwave Radio System: System Considerations," B.S.T.J., this issue, pp. 2085–2116.
3. Fenderson, G. L., "TH-3 Microwave Radio System: The IF Main Amplifier," B.S.T.J., this issue, pp. 2195–2204.